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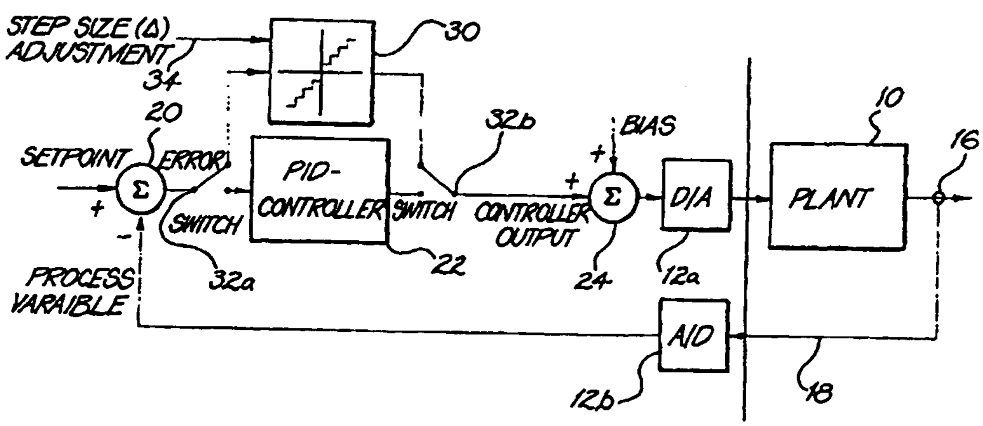

(57) Abstract

A method of tuning a PID-regulator (22), or variants thereof, of a plant (10), in which the plant (10) in a feedback system is brought into controlled self-oscillation whereupon the amplitudes and the frequency of the self-oscillation are determined and the controller (22) is tuned in dependence of the values determined for the amplitude and the frequency of the self-oscillation, wherein self-oscillation is induced by connecting in the feedback system a quantiser function (30). Quantiser functions are staircase functions $y=Q(x)$ where an output signal y_k, $k\epsilon N$, assumes a predetermined discrete value out of a finite set of discrete values for each of plurality of input signal values $X\epsilon R$ within a predetermined interval of input signal values. That is, each discrete output signal value is associated with a plurality of input signal values within a specific one interval.

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METHOD AND APPARATUS FOR AUTOMATED TUNING OF PID CONTROLLERS

Technical field

The present invention relates to the tuning of regulators or controllers, in particular PID-type controllers. The invention is concerned with a method which enables the tuning parameters ("tuning constants") of a PID-regulator to be established by inducing the process or system to be regulated into self-oscillation in order to sample specific parameters of the oscillating process which can be used to determine or compute the tuning constants.

The invention also relates to a method and apparatus for automated tuning of PID-controllers.

Background art

The majority of regulators or controllers used in industrial processes and systems are of PID-type. Such regulators provide for proportional, derivative and integral control of the parameters of the process or system. A large industrial plant may include hundreds of such regulators. In many instances, while PID-regulators are installed, only part of their control functions, i.e. derivative and proportional (PD), are employed to regulate a specific part of the overall process in the plant, and it is thus common to encounter PI-, PD- or P-only controllers which can be considered a special case of PID-control where the appropriate control function is set to zero (e.g. PI- is PID with D = 0).

With the advent of computers, a tool has been provided to control designers and engineers to implement more complicated control functions beyond that provided by conventional PID-controllers. PID-controllers are generally based on the assumption that a process is linear over a small region near a desired operating point. It can be shown that an ideal PID-controller is the best controller for chemical processes and mechanical systems which can be described by first- and second order system equations, see i.e. Harris Chemical Engineers Handbook, 6th Edition, McGraw-Hill International Editions, Section 22 "Process Control".

Another reason why the vast majority of controllers still use the basic structure of a conventional PID-controller even if the regulator is

embodied in a programmable micro-computer allowing more complex control algorithms, is that persons of skill in process technology have long standing experience with and a "feeling" for the tuning of PID-regulators.

Fig. 1 shows in diagrammatic fashion a typical feedback circuit where a PID-controller is employed to regulate one or more parameters of a process or system ("the plant"). The plant to be regulated is indicated at block 10. Interfaces 12a, 12b serve to establish communication and data exchange links between the physical system of the plant and a digital computer 14 in which the PID-control algorithm is implemented. The interfaces 12a, 12b are analog-to-digital (A-D) and digital-to-analog (D-A) converters. These A-D and D-A elements usually reside within the digital computer system 14, although in more recent time they have been incorporated within the sensors and actuators on the physical plant side, e.g. where a common field bus is used. The plants' parameter (or parameters) which it is required to control ("controlled or process variable") is sampled at the plant output at 16 by a sensor and fed via line 18 to the computer 14 where it is translated to digital form by the A-D converter 12b. The controlled or process variable is compared to a set-point ("reference value") at comparator 20 and the difference between the two quantities is used to create an error or controller actuating signal. The error signal drives the PID-controller 22 in known manner (refer to above prior art reference) which in turn produces a controller output signal, also referred to as the manipulated variable. The controller output signal is then either converted directly to analog form by D-A converter 12a to drive appropriately located actuators to adjust the plants controlled variable, or alternatively conversion takes place after it has been combined at summing point 24 with a predetermined bias value. Bias is unnecessary where full integral control is performed, since this provides for automatic reset or bias. In essence, the manipulated variable is adjusted by the PID-controller based on the error signal and the tuning parameters of the PID-controller in order for th controlled or process variable to be as close as possible to the reference value.

As stated above, while such PID closed-loop control circuit

provides adequate regulation for a vast number of control problems that are encountered in practice, one of the major tasks in implementing PID-control is finding the best proportional (P), integral (I) and derivative (D) tuning constants for any given control application. These tuning constants are process dependent and may, in fact, change from time to time.

There are well established methods for the manual tuning of PID-regulators dependent upon the parameters of the plant, e.g. the method of Ziegler and Nichols, see "Optimum Settings for Automatic Controllers", Transactions of the American Society of Mechanical Engineers, pp.759-768, 1942. In spite of the availability of a number of different methods for finding the tuning constants, see also D.E. Seborg, T.F. Edgar and D.A. Mellichamp, "Process Dynamics and Control", John Wiley & Sons, 1989, the majority of PID-controllers are badly tuned in practice.

Two factors are mainly responsible for poor tuning. These are:

i) manual tuning is a time consuming operation which comprises manually changing the regulator amplification until self-oscillation of the process can be observed, thus allowing the determination of the tuning constants; and

ii) the level of expertise required for such manual tuning is often outside the skill base of the persons actually assigned to do the task.

A number of "self-tuning" or "auto-tuning" procedures have been developed over the past few decades in order to deal with the problems associated with manual tuning of PID-controllers. Many of these "self-tuning" techniques are based on adaptive control ideas as described by G.C. Goodwin and K.S. Sin in "Adaptive Filtering Prediction and Control", Prentice-Hall, 1984. The equipment used for such automatic tuning of PID-regulators is expensive and not quite simple to use. Moreover, adaptive regulators are much more complicated than a simple PID regulator and far too complex for general use. This is one of the reasons why they have only found limited use.

One approach in "auto-tuning" of PID-controll rs that has received considerable attention is the so-called relay auto-tuning method ("RAT-Method") developed by K.J. Åström and T. Hägglund and which is the

subject matter of US patent 4,549,123, the contents of which is incorporated herein by way of short hand cross-reference. An "Auto-Tuner" in accordance with the RAT-method is presented in "Automatic Tuning of Simple Regulators with Specifications on Phase and Amplitude Margins", Automatica, Vol. 20, No. 5, pp 645-651, 1984.

In summary, the RAT-method involves temporarily replacing the PID-controller with a non-linear relay function generator. The relay provides an on-off, or two-position control mode such as commonly found in thermostats used in space heating, refrigeration and the like. For a description of on-off type control of a plant, see Perry's Chemical Engineers Handbook, above, Section 22-14. The non-linear relay function is used to induce a sustained oscillation of the process or controlled variable through the closed-loop feedback circuit in replacement of the PID-controller illustrated in Fig. 1. This is also referred to as the plant being (controlled to be) in self-oscillation. In contrast, in tuning the regulator by means of the method of Ziegler and Nichols a linear or proportional function is used to induce self-oscillation of the plant (more precisely, the controlled variable). While the plant is in self-oscillation, the amplitude and frequency of the controlled variable are determined by appropriate sensors arranged at the system output (preferably at the junction of the feedback line from the physical system to the controller). With these two parameters, it is possible to determine the ultimate gain and ultimate frequency, (also called the critical point), as defined by Ziegler-Nichols and these values in turn can be used to either calculate or look-up in a priorly sampled look-up table the proportional, integral and derivative tuning constants for the PID-controller.

Due to the simplicity of this approach, it has been suggested that this procedure can be automated and consequently an "auto-tuner" is obtained. One additional aspect that has been addressed by Åström and Hägglund is the use of hysteresis in the relay function in order to ameliorate chattering problems associated with noise interf rence signals.

Notwithstanding the considerable interest by control researchers and control practitioners in the RAT- method, there are few reported cases of where this procedure has been truly automated. Also,

there are some inherent problems associated with the RAT-method:

(a) The PID controller must be bridged or taken out of service and replaced by the relay function generator for tuning purposes. This task is not as straight forward as it may seem as it entails removing PID-control from the plant for the time period required to sample oscillation parameters. As is self-evident, this can lead to loss of control over the plant during the tuning procedure when carried out on-line.

(b) One point which is often not addressed when using the RAT-method is that a bias or manual reset value has to be supplied to and combined with the output signal from the relay function generator in order to centre the average process variable around a desired set point. This can be explained in that replacing the PID-controller by the relay function generator in average is similar to proportional-only feedback control which always introduces an off-set value in the process variable. The required bias value will be determined by the average load (disturbance) on the physical plant. Finding this bias value may be difficult to do in an on-line situation, particularly when the plant has a fast response time.

(c) The load conditions of the plant may change during the PID regulator tuning procedure. This can render the previously established bias value unsuitable for the new condition. Once again, this can lead to unstable conditions with subsequent loss of control.

(d) As stated above, the integral control function provided by the PID controller eliminates steady state off-set error. Therefore, the integrator stage of the PID controller can be interpreted as a time-varying bias or automatic reset. Accordingly, the action of switching from the PID controller to the relay function generator during the tuning procedure may not result in a "bumpless" transition of control (e.g. removal of self-adjusting bias) and this is often a major hindrance in practice for control safety reasons.

Summary of the Invention

In light of the above, it would be advantageous if the present invention could provide a method of tuning a PID-regulator, or variants thereof, which can be automated and implemented in an apparatus. It

would be advantageous for the invention to ameliorate or completely avoid one or more of the above mentioned disadvantages perceived with the RAT-method and apparatus.

Broadly, this can be achieved by a method in which the plant (more precisely the controlled or process variable) in a feedback system is brought into controlled self oscillation by applying an alternate, non-linear function different from a relay function to enable measurement of critical points of the plant during oscillation which can be used for determining the tuning constants with known methods.

In accordance with the invention, so-called quantiser functions are employed to achieve self-oscillation of the plant. Quantiser functions are stair-case functions $y=Q(x)$ where an output signal y_k, $k \epsilon N$, assumes a predetermined discrete value out of a finite set of discrete values for each of a plurality of input signal values $X \epsilon R$ within a predetermined interval of input signal values. That is, each discrete output signal value is associated with a plurality of input signal values within a specific one interval.

In the present context of controllers and where a quantiser function generator replaces the relay controller of the RAT-method, the input signal to the quantiser generator is the controller actuating or error signal and the output signal is the manipulated "quantiser" output during the tuning procedure.

Brief description of the drawings

Fig. 1 is a highly schematic block diagram illustrating a typical feedback system where a PID-controller is used to regulate one parameter of a plant;

Fig. 2a - 2d exemplarily illustrate four different types of quantiser functions which in accordance with the invention can be used to induce self-oscillation in the feedback system of Fig. 1 to calculate the tuning constants of the PID-controller;

Fig. 3 illustrates a preferred quantiser function of uniform, mid-tread type generated by a quantiser function generator switched into the feedback system of Fig. 1;

Fig. 4 illustrates a modified quantiser function in accordance with

Fig. 3 where hysteresis has been introduced;

Fig. 5a illustrat s in highly schematic, block-diagram form one preferred feedback system where a quantiser function generator is arranged parallel with the PID-controller to induce self-oscillation;

Fig. 5b illustrates in highly schematic, block-diagram form one preferred feedback system where a quantiser function generator is arranged in-line with the PID-controller to induce self-oscillation; and

Fig. 6 is a highly schematic block diagram of same kind as Fig. 1 showing one preferred form of the invention embodied in an automated self-tuning PID-regulator based on a micro-computer.

A further understanding of the nature, different aspects, preferred forms and advantages of the invention may be realised by referring to the ensuing portions of the specification and with reference to the accompanying drawings.

Description of the Preferred and Other Embodiments

Turning initially to Figs. 2a and 2d, there is shown a number of quantiser functions which may be used in accordance with the invention. The set of possible discrete values which the output signal provided by a quantiser function generator $y = Q(x)$ can assume is described by:

$$Y \epsilon \{Y_1, Y_2, \ldots, Y_k, \ldots Y_{L-1}, Y_L\}$$

In Figs 2a - 2d, L is limited to 7 and 8. All of the illustrated step functions are symmetric about zero, this, however, not being a limiting necessity as far as the invention is concerned. The quantiser function of Figs. 2a and 2b are "non uniform", with intervals $Y_{k+1} - Y_k$ and $X_{k+1} - X_k$ being different in length and functions of k.

The quantiser functions of Figs 2c and 2d are "uniform" with the intervals $Y_{k+1} - Y_k = X_{k+1} - X_k = \Delta$, where Δ is defined as the step size.

The characteristic of $y = Q(x)$ can also be of "midtread" or "midrise" type, depending on whether zero is one of the output signal levels. For symmetry purposes, L is chosen to be an odd natural number for midtread quantisers.

A preferred quantiser function in the context of the present invention is characterised by the equation:

$$Y = \{(2\left[\frac{X}{\Delta}\right] + 1)\frac{\Delta}{2}\}\ sgn(x)$$

where :

Y represents the output value of the signal of the function generator ("quantiser output"),

X is the input value received by the function generator, eg the error signal,

Δ is the step size and chosen to be independent of the input (uniform quantiser function),

$[\frac{X}{\Delta}]$ is the greatest integer of the function $\frac{X}{\Delta}$,

and sgn (x) is the signum of x.

This preferred function is illustrated in Fig. 3.

One reason for the preference of a uniform quantiser function with midtread characteristic is the symmetry of quantiser output values for positive and negative input signal values and more importantly the necessity to only control or change one variable the step size Δ, in order to adjust the quantiser output signal to induce self-oscillation of the plant, as will be described herein below.

The quantiser output signal will therefore assume any one of the discrete values Δ/2, 3Δ/2, 5Δ/2... in response and depending on the magnitude of the input value, i.e. error signal value.

Upon self-oscillation being induced by application of the quantiser function in the feedback system, a critical point on the Nyquist curve can easily be determined in known manner. It is then straightforward and well known to apply classical Ziegher-Nichols controller tuning rules. It is also possible to apply other known design schemes that are based on the knowledge of one or more points of the Nyquist curve. Algorithms for automatic tuning based on amplitude and frequency margin criteria are well known (see Åström and Hägglund, above) and these can be

employed to determine the tuning constants of the PID-regulator. It is to be cl arly understood that the present invention does not purport to provide new design or algorithm schemes for ultimately calculating the tuning parameters. The present invention provides a way to induce self-oscillation of the system in feedback whereby control of the plant can be maintained, and the tuning parameters can then be calculated using known algorithms once one or more critical points (frequency/period and amplitude) of the oscillating system are determined.

In a first application of the invention there is provided a method of tuning a controller for a process in a feedback system, including the following steps:

- providing a function generator arranged to receive an input signal and supply an output signal in accordance with a staircase-function, the generator arranged in-line after or parallel with the controller in the feedback system;
- applying the output signals from the staircase function generator to the process such as to achieve self-oscillation of the system;
- determining at least one amplitude and at least one frequency of the system in self-oscillation;
- determining predetermined controller parameters by having reference to the at least one amplitude and one frequency; and
- tuning the controller with the controller parameters.

In the above method, while different types of staircase or quantiser functions can be employed, such as mid-step or mid-rise, uniform or non uniform, a preferred quantiser function is a uniform mid-rise quantiser as i.e. illustrated in Fig. 3.

The PID tuning method differs from the RAT-method in that the quantiser output signal can take one of a plurality of discrete values Y_k, not just two, as is the case with a relay. The quantiser generator can provide outputs which span very large positive and negative values (practically $\pm\infty$ as is hinted to in Fig. 3), since it does not need to have overload regions. Thus, it is not limited to a preset range of two relatively small output values as is the case with a relay.

As was discussed with reference to the prior art RAT-method,

noisy signals can also be taken care of with the tuning method in that the quantiser function generator can be adapted to provide modified output signals having regard to a hysteresis factor h. A modified staircase function with hysteresis is illustrated schematically in Fig. 4. The use of hysteresis in control signals is common practice in the field of controllers and its working will not be described further.

The step function generator can be further arranged such that the step size Δ and, in case of a non-uniform quantiser function, the size of the quantiser intervals $Y_{k+1} - Y_k$ can be varied to ensure that the process can be brought into self-oscillation outside the noise band signal levels.

In a first embodiment of the first application as illustrated in Fig. 5a, the quantiser function generator 30 is arranged in parallel with the controller, e.g. PID-controller 22, such that it can be switched through switches 32a, 32b into the feedback system in replacement of the controller 22. With this arrangement it is possible to determine the controller parameters in similar fashion as was described above with reference to the RAT-method and Fig 1. The quantiser function generator output signal will induce an oscillation similar to that of the relay in the RAT-method, which oscillation will be dependent on the step-size Δ, which can be adjusted at 34.

The amplitude and period of the feedback system comprising the plant, the feedback line, the set point comparator, the quantiser function generator and the AD/DA converters during self-oscillation can then be used to find the PID-tuning constants as in the RAT-method, i.e. having recourse to the Ziegler-Nichol or other known methods. The necessary algorithms can be implemented in known manner in a micro-computer.

Alternatively, two (or more) sets of critical amplitudes and frequencies can be determined for different Δ-steps, and a least square model can then be fitted to the two (or more) values on the Nyquist-curve corresponding to the amplitude and frequency value sets. Subsequently, the model can be reduced in known manner to "design" the PID-controller (e.g. determine the tuning constants P, I and D) i.e. via Pole-placement, Internal Model Control design techniques or in accordance with any one of a number of known techniques. Reference should be made to

available literature which describes such techniques, i.e. K.J. Åström and B. Wittenmark, "Computer Controlled Systems: Theory and Design", Prentice Hall, 1984 and M. Morari and E. Zafiriou, "Robust Process Controll" Prentice Hall, 1989).

Once the PID controller tuning constants have been determined, and the PID-controller adjusted accordingly, the quantiser function generator 30 is taken off-line or removed and instead the PID controller 22 brought in-line.

The advantage of this method as compared with the RAT- method is that there is no need to determine a precise bias value since quantiser functions can cope with some proportional off-set in input signal, that is, a "bias" value will be provided automatically by virtue of the fact that the process will attain self-oscillation within the most appropriate level of quantiser intervals.

Further, if a load change occurs in the plant during the tuning procedure, the quantiser function generator signal will change to a different quantiser interval level in response to a change in level of the error input signal received at the quantiser function generator. This is equivalent to a change of bias value and the quantiser function generator output will be brought in conformity with the error signal change due to load variation in the plant.

These two advantages address two of the above-mentioned problems which the RAT-method has, namely, the necessity to provide a separate bias value to cater for the off-set value in the controlled variable introduced by relay function control, and the necessity to find separate bias values upon load disturbances on the plant.

In a second, preferred, embodiment of the first application of the invention, the quantiser function generator is arranged in series between the controller (e.g. PID-controller) and the plant, and the quantiser function generator is used to bring the closed loop system into self-oscillation while the PID-controller is on-line, that is producing a controller output signal. One such possible arrangement of the quantiser function generator in a typical feedback system where the PID controller is employed to regulate one or more parameters of the plant, is

diagrammatically illustrated in Figure 5b, where same reference numerals have been used as in Figure 5a. The advantage of this arrangement is that no switching between PID-controller 22 and quantiser function generator 30 needs to take place during the PID-controller tuning procedure. This avoids above-mentioned problems associated with removing the PID-controller from the control circuit of the plant during tuning procedures and ensures a smooth transition of control during tuning procedures.

Furthermore, the above-mentioned finding of a suitable bias value necessary for proper operation of the RAT-method is no longer necessary since the integral component of the PID-controller will provide automatic self-centring of the average process variable around the desired set point value.

Finally, if a load change occurs in the plant during the tuning procedure, the manipulated variable which is provided by the quantiser function generator to the plant will either be maintained at a constant value or changed to a predetermined one of the possible discrete quantiser output values which will prevent loss or control following a load disturbance. When the load disturbance is such that the associated change in process variable value will correspond to only a small change in error signal, the PID-controller output (which determines the level of the quantiser input signal) may still fall within the same quantiser step interval which also applies to the undisturbed process variable value. Thus, no change in quantiser output level will take place, and the plant will be maintained in controlled self-oscillation regardless of the load disturbance. On the other hand, when the load disturbance is such as to affect the error signal to such an extent that the PID-controller output (equivalent to the quantiser input level) will correspond to a different quantiser output level, then the quantiser function generator will generate a changed output signal to counter the effect the load disturbance has on the plant, thus maintaining control. Further, the PID-controller's internal automatic reset (int gral function) will restore the average process variable to the correct region of operation and no loss of control can occur.

When the generator 34 is arranged to operate with a uniform, mid-rise quantiser function as illustrated in Figure 3 or 4, sustainable self-oscillation of the plant 10 can be induced in a simple way by increasing the step size Δ, as indicated schematically at 34, from a first small value to a second value in which self-oscillation is present and clearly observable. As stated above, with uniform, mid-rise quantiser functions, the quantiser interval is equal and directly coupled with the step size Δ such that only Δ need be manipulated. While self-oscillation will also be present when the step size Δ and its corresponding quantiser output level is small, it is necessary to ensure that the step size has such a value that the sustained self-oscillation of the process variables is clearly discernible as being induced by the quantiser function generator and not within normal noise bandwidth oscillations. That is, the step size needs to be increased to such a value where sufficient fidelity of measurement of the amplitude and frequency of the oscillating process variable is achieved.

As stated, the quantiser function generator in this case can be operated to induce a sustained self-oscillation as is the case where the quantiser function generator is arranged in parallel and in substitution of the PID-controller. Therefore, in this embodiment also, the tuning method relies on determining at least one set of amplitude and frequency values during oscillation as has been previously described. With these two measured parameters (or a plurality of such value pairs) it is then possible to identify one or more points on the Nyquist diagram (using frequency response tuning methods) which is related to and can be used to calculate key parameters from which the PID tuning constants can be determined, i.e. by means of conventional look-up tables or specific design formulae. It should be noted, however, that the frequency and amplitude measured, in the case where the PID-controller is arranged in series with the quantiser function generator, are different to the case where the PID-controller is replaced by the quantiser function generator, since the controller dynamics also have an effect on the closed-loop system which will have to be accounted for when determining the PID tuning constants. This, however, is no problem to an experienced controller designer.

Once the tuning parameters have been determined and the PID-controller accordingly tuned, the step size Δ of the quantiser function generator will be reduced to a level where self-oscillation is no longer be appreciable or, preferably, the generator provides an input equals output signal.

It is advantageous, though not essential, that the mark to space ratio of the quantiser output signal is equal to 1. This can be achieved by trimming the error signal with an additional "errortrim" as provided for at summing junction 36 in Figure 5b.

Advantageously, during the tuning procedure, the step size of the quantiser function should be increased gradually from a first small value to a second value where the self-oscillation is maintained within the same quantiser level.

Alternatively, during the tuning procedure, the step size Δ of the quantiser function can be increased from the small value to the second value such that self-oscillation is maintained within any one quantiser output level.

As will be appreciated, an initial tuning procedure can be carried out when the plant is off-line to provide a first set of tuning parameter P, I, D for the controller, and subsequent re-tuning can be carried out on-line, repeatedly if necessary, to adapt the controller to a changing plant process.

<u>Mode for Carrying Out the Invention</u>

In the following, a description of a PID-controller with automatic tuner in accordance with a second aspect of the invention will be provided with reference to Figure 6.

The PID-controller and automatic tuner functions, as well as all other control algorithms are implemented on the basis of a digital micro-computer which is illustrated in the block diagram of Figure 6 at 14. On the input side from the plant 10, the self-tuning PID-controller 14 has an A/D-converter 12b and on its plant output side a D/A-converter 12a. A further input is provided for the set point value for the process variable as indicated schematically on the left hand side of Figure 6. The self-tuning PID-controller 14 includes a CPU 40 which communicates with an

autotuner unit 50 (which will be described hereinbelow) and a controller unit 22 which provid s the PID- functions. The controller unit 22 includes a programmable read only memory (PROM) serving as a program storage for the proportional-, integral-, and derivative control algorithms to provide the PID-control functions. The digital computer 14 will further include a number of buffer memories with input and output registers as well as clock signal generators (not illustrated) for the internal data transfer within the computer and for the converters 12a, 12b. The units 40, 50 and 22 are combined to cooperate in a known manner, and while the block diagram of Figure 6 shows individual lines running between different components (units) of the self-tuning PID-controller 14, these are illustrative only to show data exchange between the different units. It will be appreciated that a common bus may serve all units for data and signal interchange. As further illustrated in Figure 6, a quantiser function generator unit 30 is arranged in line between the PID-controller unit 22 and the D/A-converter 12a as was described with reference to Figure 5b.

In the embodiment of Figure 6, the PID-circuit functions are stored in the PROM of the controller unit 22 as algorithms for acting upon the controller input signal i, which is a combination of the error trim signal and the error signal, as was described with reference to Figure 5b, in order to generate a controller output signal c which is supplied via the quantiser function unit 30 and D/A-converter 12a to the plant 10.

An appropriate quantiser function, i.e. having the characteristics illustrated in Figure 3 or 4, is stored in unit 30 as an algorithm for acting upon the output signal c as described hereinbelow. An operator interface may be provided to enter the required quantiser parameters, in particular the step size Δ. Also, control algorithms may be provided to automatically adjust Δ in response to specific operational conditions (i.e. tuning operation vs normal operation) of the self-tuning PID-controller 14. During normal operation (other than during tuning procedures) the quantiser unit 30 is set so that input = output signal (i.e. $\Delta = 0$) and the controller output c will be supplied to the plant 10 to control the process in conventional manner. Like with the embodiments of Figures 1 and 5, the process' actual value or controlled variable is sampled at 16 and

combined with the inputted reference value (set point) at summing junction 20 to provide the error signal driving the controller 22.

When the PID-controller is to be tuned, (that is the P, I and D tuning constants determined), the feedback system for determining the measured quantities of amplitude and frequency during self-oscillation is brought into self-oscillation in that the quantiser function $Y = Q(X)$ where $X = c$, and $Y = l$ (quantise output level), is coupled into the signal path from the controller unit 22 to the output D/A-converter 12a so that the quantiser unit output signal "overrides" the controller output c to induce self-oscillation. Heretofore, the auto tuner 50 incorporates algorithms that enable it to compute:

a) a suitable step size Δ as a function of the process variable measured at 16 and digitalised at 12b, controller output c and quantiser output level l;

b) a suitable error trim as a function of the step size Δ and quantiser output level l; and

c) an appropriate hysteresis factor h to counter chattering in the signal.

The actual measuring of the amplitude and frequency of the oscillation is not part of the invention but any suitable method of measurement can be used. For measuring the amplitude, in example, the amplitude of consecutive oscillations can be measured and an amplitude value is set to be a critical amplitude when subsequently measured amplitudes differ in value less than a predetermined amount i.e. 1-5%; alternatively, the method of recursive least squares identification may be used; or a Kalman filter. The frequency can also be determined in several ways, i.e. by measuring the time between consecutive zero-crossings of the oscillation, applying a method of recursive least squares or using a so-called extended Kalman filter which enables determination of both amplitude and frequency using the same filter. These functions are implemented as algorithms in the "PID Calculus Algorithm" unit of the auto-tuner 50 together with appropriate algorithms which allow determination of the individual P, I and D-tuning parameters according to known formulae.

The auto-tuner unit 50 can be devised such that tuning will automatically tak place at predetermined time intervals, or upon being triggered by an event, i.e. should the process variable defer from the set point by more than a predetermined "re-tuning" value. As stated above with reference to Figure 5b, once the tuning procedure is finalised and the PID-parameters determined, the step size Δ will be reduced to 0 such that controller output c = quantiser output, and the plant will be controlled in normal fashion by the PID-controller unit 22.

The above described new adaptive mechanism for PID-controller tuning NAMPID is simple and can be incorporated by way of a few program steps in a microcomputer. Furthermore, the above described PID-controller with auto-tuner can be expanded to provide self-adaptive tuning which is timer or event triggered, thus enhancing performance monitoring of the plant.

As a further refinement, the plant or equipment can be injected with additional signals in accordance with requirements to attain additional information as to the operation of the plant. For example, intermittent transients can be injected and analysed for a transient response.

The choosing of specific hardware and designing of software to provide the above specific functions are well within the skill of a control design engineer and thus need not be described here.

Furthermore, the present invention may be applied/used to tune the controller parameters in a multivariable plant having a number of manipulated variables and a plurality of outputs which may or may not be coupled or functions from one another.

It is to be understood that the invention is not limited to the embodiments described and illustrated but can be modified within the scope of the following statements of invention.

Statements f Invention

1. A method of tuning a PID-regulator, or variants thereof, of a plant, in which the plant in a feedback system is brought into controlled self-oscillation whereupon the amplitudes and the frequency of the self-oscillation are determined and the controller is tuned in dependence of the values determined for the amplitude and the frequency of the self-oscillation, wherein self-oscillation is induced by connecting in the feedback system a quantiser function.

2. A method as claimed in claim 1, wherein the quantiser function is a staircase function with uniform characteristics.

3. A method as claimed in claim 2, wherein the quantiser function is of mid-tread type.

4. A method as claimed in any preceding claims wherein the quantiser function is characterised by the equation:

$$Y = \{(2\left[\frac{X}{\Delta}\right] + 1)\frac{\Delta}{2}\}\ sgn(x)$$

where :

Y is the quantiser output value,

X is the input value,

Δ is the step size,

$[\frac{X}{\Delta}]$ is the greatest integer of the function $\frac{X}{\Delta}$,

and sgn (x) is the signum of x.

5. A method of tuning a controller for a process, in particular a PID-controller or variants thereof, including the following steps:

- arranging the controller in a feedback system with the process;
- arranging a means for providing a quantiser function in-line or parallel with the controller;
- applying the non-linear quantiser function to the process such as to bring the closed loop feedback system into self-

oscillation;

- determining at least one amplitude and at least one frequency of the system in self-oscillation; and

- tuning controller parameters using the at least one amplitude and one frequency.

6. A method as claimed in claim 5, wherein the tuning of controller parameters is carried out in accordance with Ziegler Nichols rules, Pole-placement design or Internal Model Control rules.

7. A method as claimed in claim 5 or 6, wherein the quantiser function is of mid-tread and uniform characteristic having a step size Δ.

8. A method as claimed in claim 5, 6 or 7, wherein the quantiser function is arranged in parallel with the controller; wherein the quantiser function is switched into the closed loop system in replacement of the controller and a step size Δ is set to obtain self-oscillation; wherein the quantiser function is removed after at least one amplitude and one frequency of the system under self-oscillation have been determined and the controller parameters tuned; and wherein the controller is subsequently replaced for the quantiser function.

9. A method as claimed in claim 5, 6 or 7, wherein the quantiser function is arranged in series with the controller in the closed loop system; wherein self-oscillation of the system is induced in that the step size Δ of the quantiser is increased from a first small value to a second value in which self-oscillation is present; and wherein the step size Δ is subsequently reduced to a level below that where self-oscillation is discernible and after the frequency and amplitude have been determined and the controller parameters tuned.

10. A method as claimed in claim 5, 6 or 7, wherein the quantiser function is arranged in series with the controller in the closed loop system; wherein self-oscillation of the system is induced in that the step size Δ is gradually increased from a first small value to a second value where self-oscillation is maintained within any one quantiser interval; and wherein the step size Δ is reduced subsequent to the frequency and amplitude being determined and the controller parameters tuned.

11. A method as claimed in any preceding claim wherein the steps of the method are carried out once for tuning of the controller.

12. A method as claimed in any preceding claims 1 to 10, wherein the steps of the method are carried out repeatedly for adapting the controller to a changing process.

13. A method as claimed in any preceding claims 12, wherein the method is implemented by way of algorithms in a computer for intermittent or event-triggered self-tuning of the controller parameters.

14. A method as claimed in claims 1 further comprising injecting further signals into said feedback system os as to gauge operational parameters of said plant.

15. An apparatus for tuning a regulator of PID-type of a process in a feedback system, the apparatus adapted to bring the system into self-oscillation such that the amplitude and the frequency of the self-oscillation can be measured and the tuning parameters of the controller be determined, characterised by means arranged to provide a quantiser function wherein an output signal assumes a predetermined discrete value out of a finite set of discrete values for each of a plurality of input signal values within a predetermined interval of input signal values, the quantiser function means arranged to be connected temporarily into the system such that the output signal induces said oscillation allowing determination of the tuning parameters.

16. An apparatus as claimed in claim 15 wherein the controller comprises a microcomputer in which the control functions of the controller are realised by means of algorithms, and wherein the quantiser function means comprises the microcomputer and the quantiser function is realised by an algorithm therein.

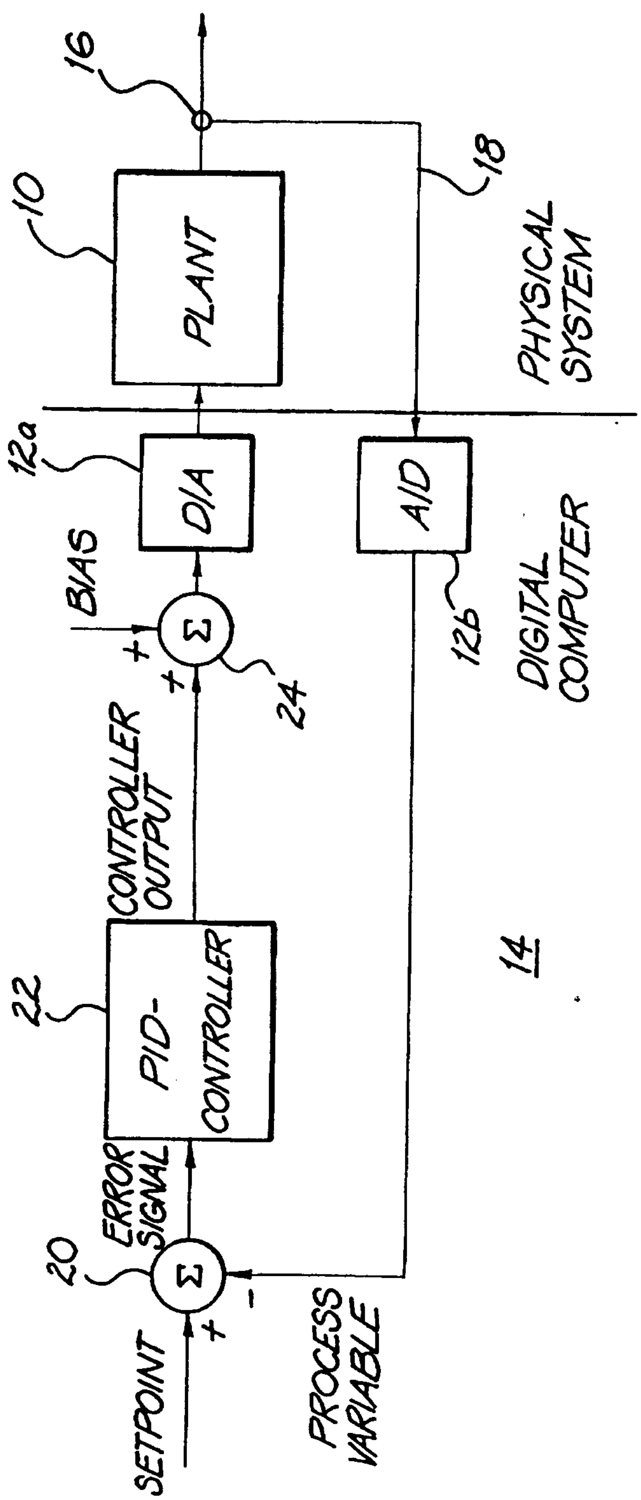

16
18
10
PLANT
PHYSICAL SYSTEM
12a
D/A
A/D
12b
DIGITAL COMPUTER
BIAS
24
CONTROLLER OUTPUT
22
PID-CONTROLLER
14
20
ERROR SIGNAL
SETPOINT
PROCESS VARIABLE

FIG. 1

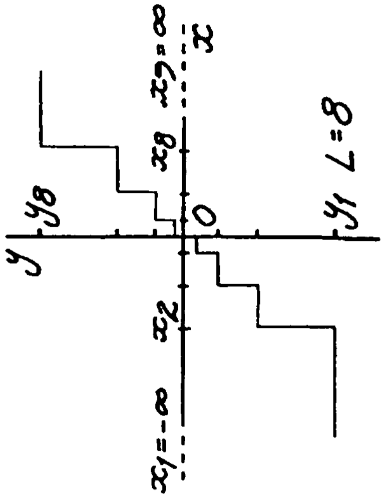


FIG. 2a

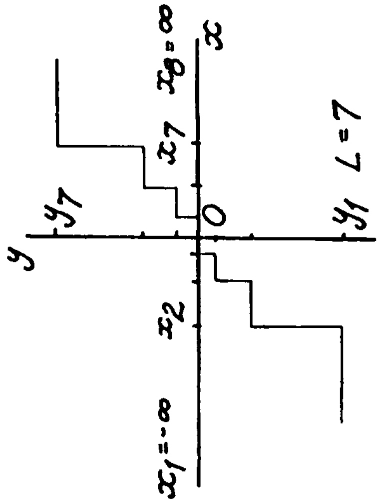


FIG. 2b

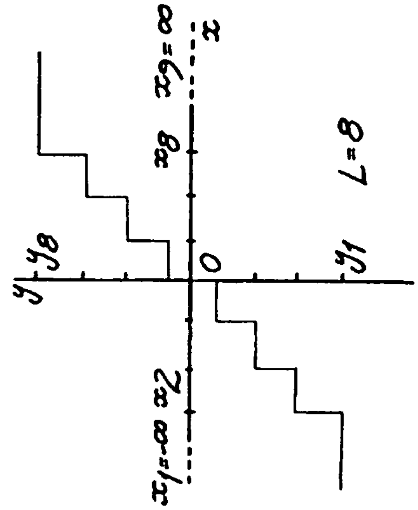


FIG. 2c

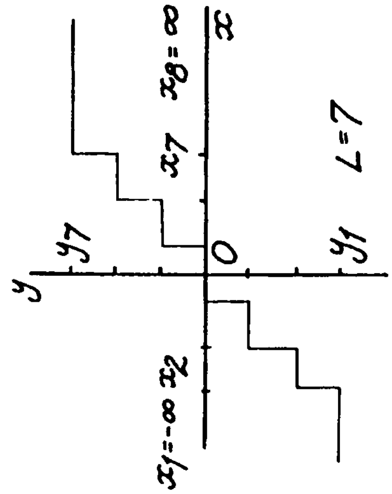


FIG. 2d

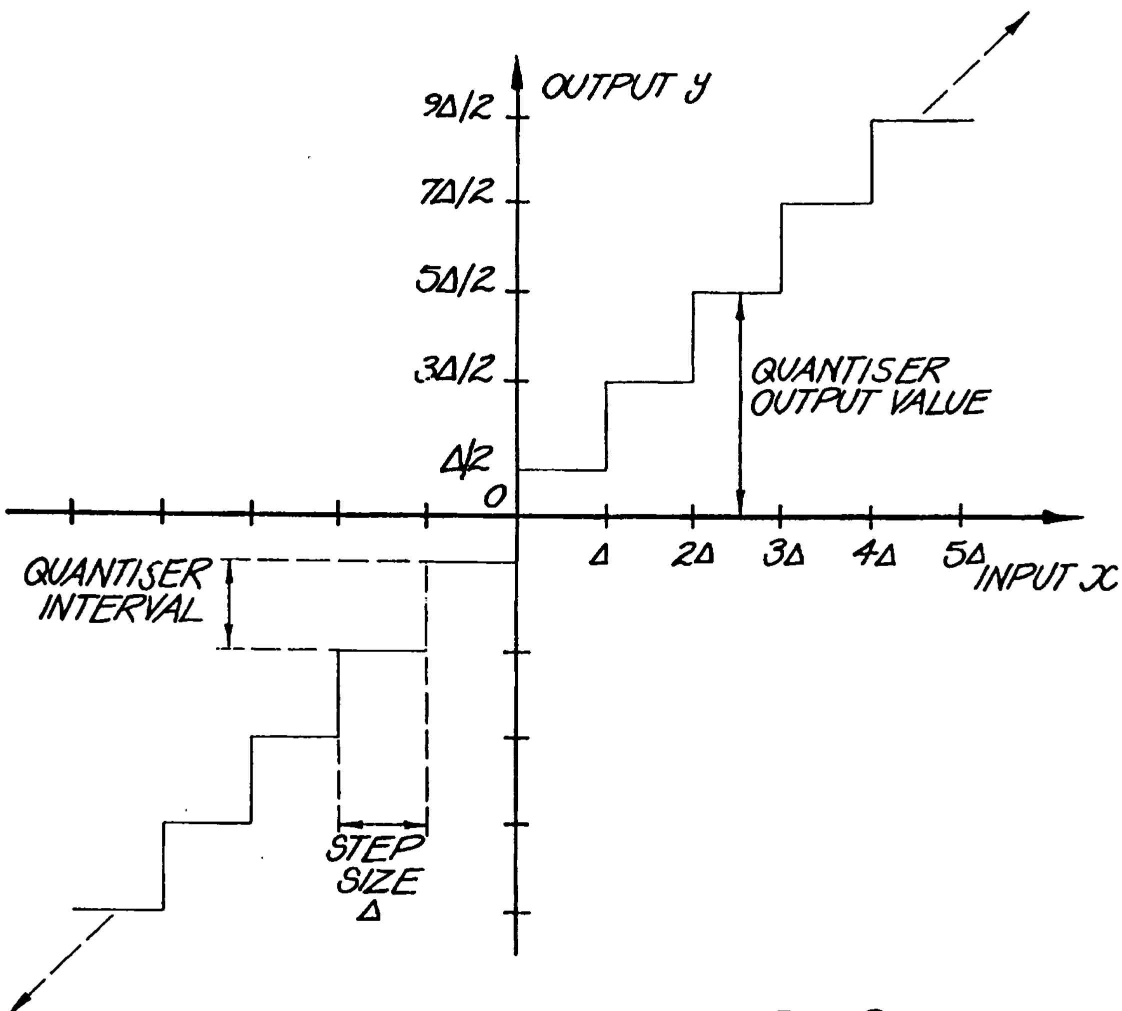

OUTPUT y
9Δ/2
7Δ/2
5Δ/2
3Δ/2
Δ/2
0
QUANTISER OUTPUT VALUE
Δ
2Δ
3Δ
4Δ
5Δ
INPUT x
QUANTISER INTERVAL
STEP SIZE Δ

FIG. 3

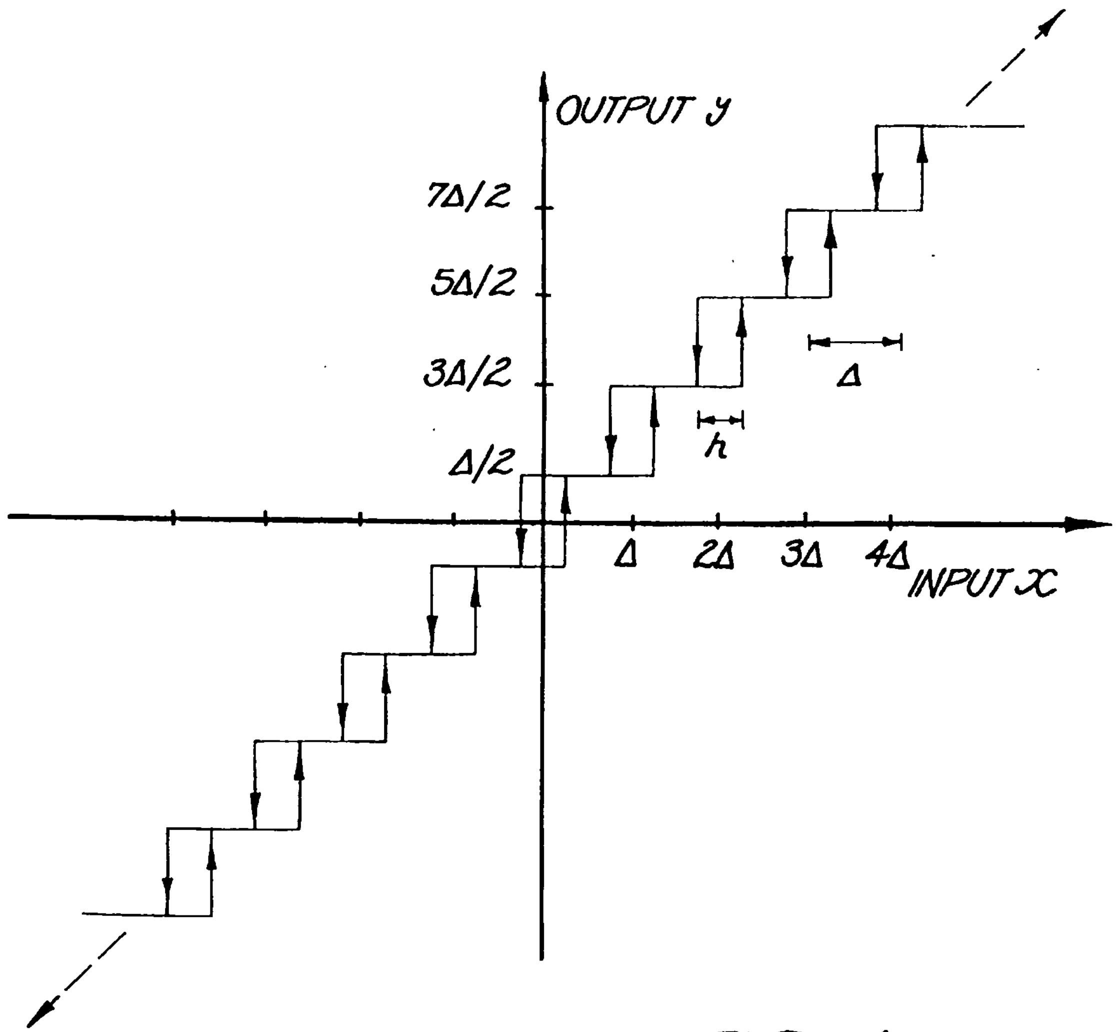


FIG. 4

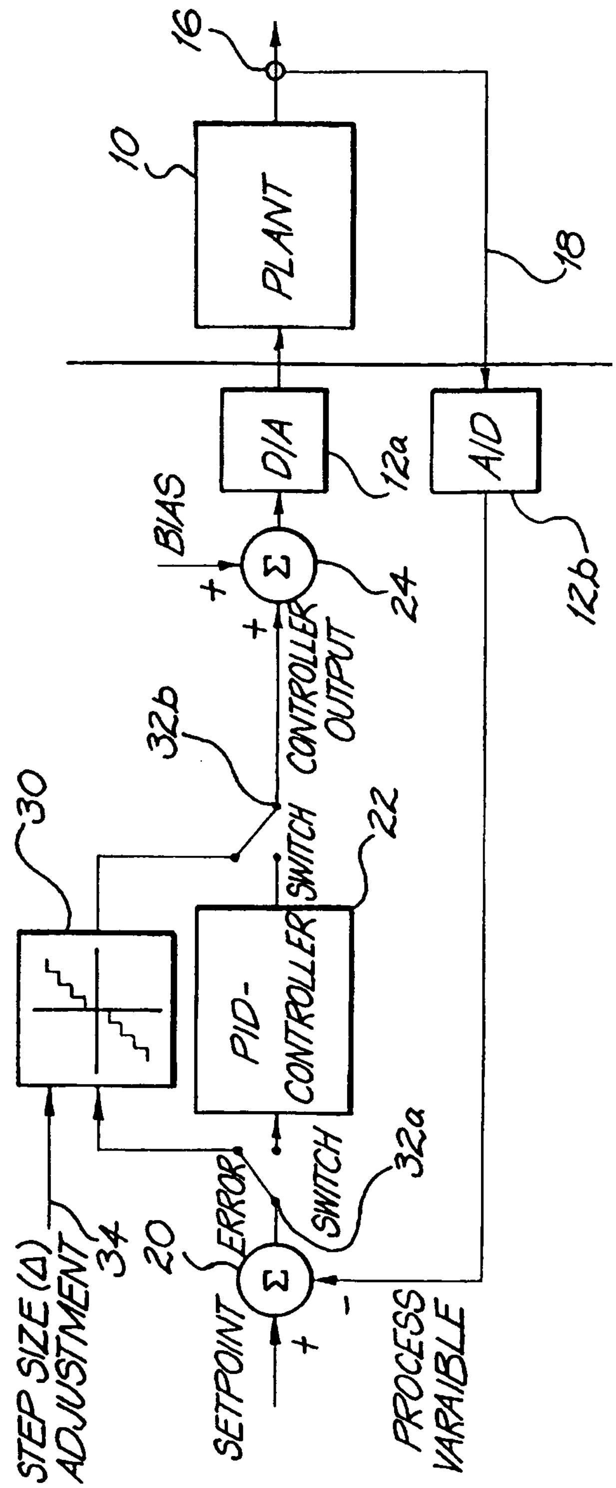
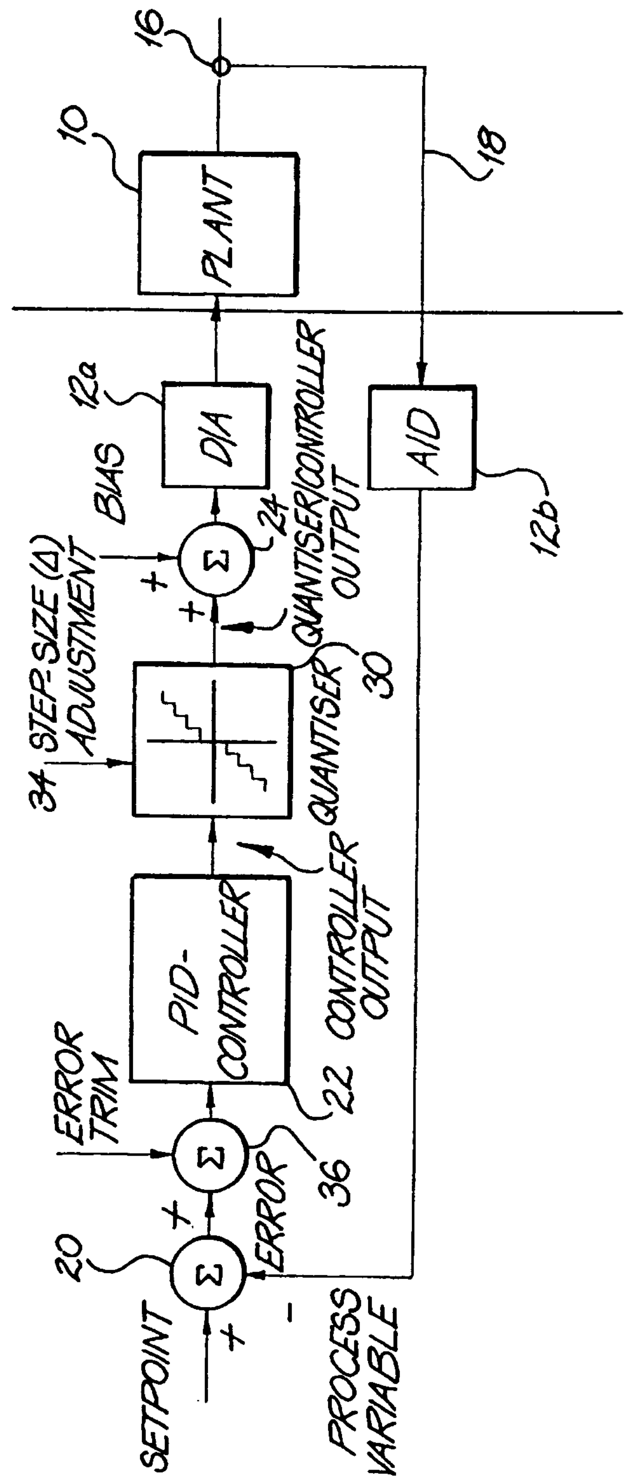

STEP SIZE (Δ)
ADJUSTMENT
34
SETPOINT
+
Σ
20
ERROR
SWITCH
32a
-
PROCESS
VARAIBLE
30
PID-
CONTROLLER
22
SWITCH
32b
CONTROLLER
OUTPUT
BIAS
+
+
Σ
24
D/A
12a
A/D
12b
PLANT
10
16
18

FIG. 5a



SETPOINT
+
20
Σ
-
PROCESS VARIABLE
ERROR
+
Σ
ERROR TRIM
36
PID-CONTROLLER
22
CONTROLLER OUTPUT
QUANTISER
34 STEP-SIZE (Δ) ADJUSTMENT
30
QUANTISER/CONTROLLER OUTPUT
+
+
Σ
24
BIAS
D/A
12a
A/D
12b
PLANT
10
16
18

FIG. 5b

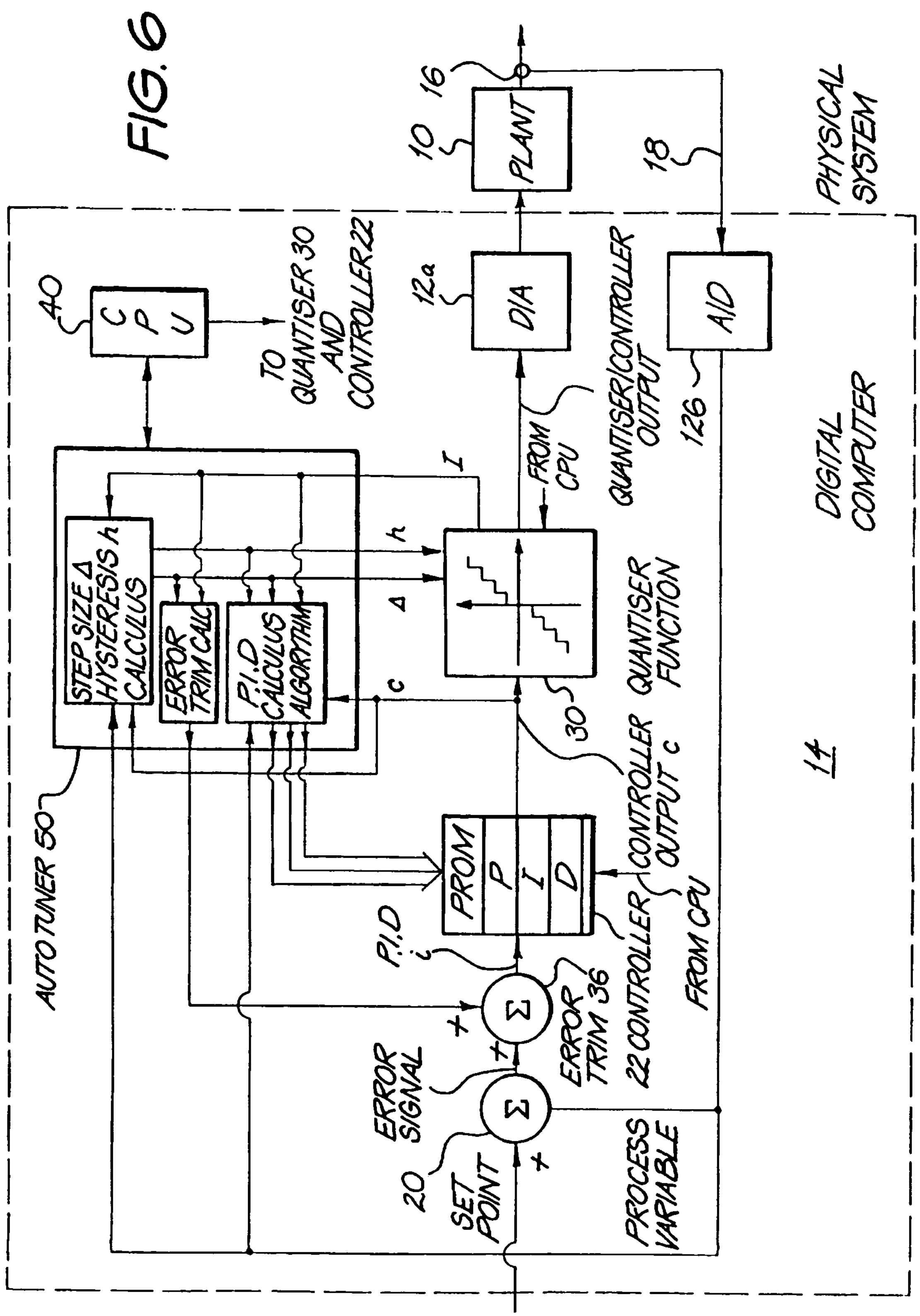

PLANT
D/A
A/D
C P U
TO QUANTISER 30 AND CONTROLLER 22
STEP SIZE Δ HYSTERESIS h CALCULUS
ERROR TRIM CALC
P.I.D CALCULUS ALGORYTHM
AUTO TUNER 50
PROM
P
I
D
FROM CPU
QUANTISER/CONTROLLER OUTPUT
QUANTISER FUNCTION
CONTROLLER OUTPUT c
22 CONTROLLER
ERROR TRIM 36
ERROR SIGNAL
SET POINT
PROCESS VARIABLE
P.I.D
PHYSICAL SYSTEM
DIGITAL COMPUTER
10
12a
14
16
18
20
30
40
126
h
Δ
c
I
Σ
+

FIG.6

A. CLASSIFICATION OF SUBJECT MATTER

Int Cl[6]: G05B 11/42, 13/02

According to International Patent Classification (IPC) r to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC: G05B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WPAT: (PIDOR CONTROLLER# OR REGULATOR#) AND (OSCILLAT:) AND (FEEDBACK)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4549123 A (HAGGLUND et al.) 22 October 1985 whole document	1-16
A	US 5229699 A (CHU et al) 20 July 1993 whole document	1-16
A	DD 272535 A (TECHN UNIV DRESDEN) 11 October 1989 abstract, figure 1	1-16

☐ Further documents are listed in the continuation of Box C

☒ See patent family annex

* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
21 October 1997

Date of mailing of the international search report
24 OCT 1997

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International Application No.
PCT/AU 97/00617

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose f information.

Patent Document Cited in Search Report		Patent Family Member					
US	4549123	CA	1201511	DK	1541/83	EP	99362
		FI	833323	NO	831435	SE	8104989
		WO	8300753				

END OF ANNEX